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Tectonic and Structural Development of Cenozoic Basins of Malaysia

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Abstract

The Cenozoic Malaysian basins are (1) located in the interior of semicratonic continental crust (Malay basin, its satellite basins, and the Penyu basin); (2) located in marginal belts of semicratonic continental crust (small, faulted depressions in the Strait of Melaka and onshore Peninsular Malaysia); (3) straddling collisional plate boundaries (Sarawak and NW Sabah basins); (4) associated with a microcontinent (Sandakan, Labuk Bay, Malawali and Tidung basins, and the circular basins of Sabah). The basin development shows the following pattern. Rifting, thermal subsidence and modification by transtensional and/or transpressional wrench faulting are the tectonic processes that operate on depressions underlain by continental crust. The crust could belong to large plates or represent a microcontinent. The basins may develop as (a) aulacogens atop a mantle-plume dome (Malay and Penyu), or (b) pullaparts where wrench faulting is the main reactivator of basement fractures. The onshore Tertiary basins of Peninsular Malaysia and the Strait of Melaka are of this type. Inverted structures are the rule, as are reversals of slip sense on the wrench faults. (c) At collisional plate boundaries, large depressions are initially formed by active subsidence of the basin floor in the subduction trench. The growing accretionary prism on the landward side of the trench wall enhances the basin depth. After subduction ceases, isostatic adjustments depresses the basin further, increasing its holding capacity. (d) The NE Sabah and Tidung basins originated as rifts in the breakup of the East Sabah microcontinent. (e) The origin and development of the circular basins of Sabah are unresolved issues. Their main features include the predominantly extensional character shown by their structures, rounded planimetric outline, and kink-like geographical distribution of which the ends are in Sandakan Bay and at Cowie Harbour.

Pembangunan Tektonik dan Struktur bagi Lembangan Kenozoik di Malaysia

Abstrak

Lembangan Kainozoik Malaysia adalah 1) terletak pada bahagian dalam kerak benua semikraton (Lembangan Melayu, lembangan berhampiran dan Lembangan Penyu); 2) terletak pada jalur pinggir kerak benua semikraton (kecil, lekukan tersesar di Selat Melaka dan daratan Semenanjung Malaysia); 3) berhampiran sempadan plat yang berlanggar (lembangan Sarawak dan lembangan UB Sabah); 4) berkaitan dengan mikro benua (Sandakan, Teluk Labuk, Malawi dan lembangan Tidung dan lembangan membulat Sabah). Berikut merupakan corak perkembangan lembangan. Rekahan, amblesan suhu dan perubahan kesan tegangan melintang dan/atau tekanan melintang sesar rengkuh, merupakan proses tektonik yang bertindak terhadap lekukan yang ditindih oleh kerak benua. Kerak ini mungkin merupakan sebahagian plat besar atau mewakili mikro benua. Lembangan ini kemungkinan berkembang sebagai a) aulakogen puncak bagi kubah selaput-mantel (Lembangan Melayu dan Penyu) atau b) 'pullaparts' dengan sesar rengkuh sebagai penjana rekahan dasar. Lembangan daratanTertier Semenanjung Malaysia dan Selat Melaka merupakan jenis ini. Struktur-struktur songsang merupakan hukumnya, manakala perulangan gelincir menunjukkan kehadiran sesar jurang. c) Pada pertembungan sempadan plat, lekukan bersaiz besar biasanya dibentuk oleh amblesan lantai lembangan di jurang subduksi. Pertumbuhan prisma akresi pada bahagian hala daratan bagi dinding jurang menambahkan kedalaman lembangan. Selepas subduksi berhenti, pembetulan isostatik melekukan lembangan itu selanjutnya, menambahkan kapasiti pegangan. d) Lembangan UT Sabah dan lembangan Tidung terbentuk semasa rekahan pada pecahan mikrobenua Sabah Timur. e) Asalan dan perkembnagan lembangan membulat Sabah merupakan isu yang masih belum selesai. Fitur utamanya termasuk struktur ekstensi predominan, rangka planimeter membulat dan sebaran geografi seakan kink dengan hujungnya di Teluk Sandakan dan Pelabuhan Cowie.

OVERVIEW

Malaysia comprises five discrete geological terranes (Figure 1). The core region or geological Sundaland includes two terranes: (1) the Western Belt of Peninsular Malaysia and adjacent Strait of Melaka, and (2) the vast region sandwiched between the (Raub-) Bentong (-Bengkalis) suture and by the Lupar suture in westernmost Sarawak. Terranes (1) and (2) are considered to have been *in situ* since the early Mesozoic, while the other Malaysian terranes accreted onto the core by subduction (terrane 3) or as a micro continent (terrane 4). The Kinabalu suture (terrane

5) marks an up to 80-km wide remnant of oceanic crust between eastern Sabah and the rest of Borneo. Episodes of vigorous and progressive closure of that palaeo-ocean are marked by Eo-Oligocene and early Miocene olistostromes. Docking of the East Sabah terrane was completed by the end of the Neogene.

Terrane 1, including the Thai Peninsula, parts of Myanmar and Sumatra (Figure 2) possesses upper Palaeozoic pebbly mudrock and cool-water fossils. The latter suggest that the pebbles embedded in the mudrock are drop stones released from melting icebergs in periglacial regions of Gondwana. Recently Lower Permian cool-water brachiopods and other marine fossils associated with pebbly mudrock were collected from the Singa Formation of the Langkawi islands and described by Shi *et al.* (1997) and Mohd Shafeea Leman (1997). The glacial origin of the pebbly mudrock of the Singa Formation was postulated some time ago (Stauffer and Mantajit, 1981; Stauffer and Lee, 1986), but the presence of cool-water fauna within Malaysia is a new finding. Most probably the Gondwana fragment of Southeast Asia rifted off northwestern Australia (Figure 1) before it drifted northward and docked along the Bentong suture. The suture, known initially as the Bentong-Raub line (Hutchison, 1975) consists of sedimentary and tectonic melanges forming an at least 18-km wide belt running North-South from the Thailand- Malaysia border along the east side of Banjaran Titiwangsa and across the

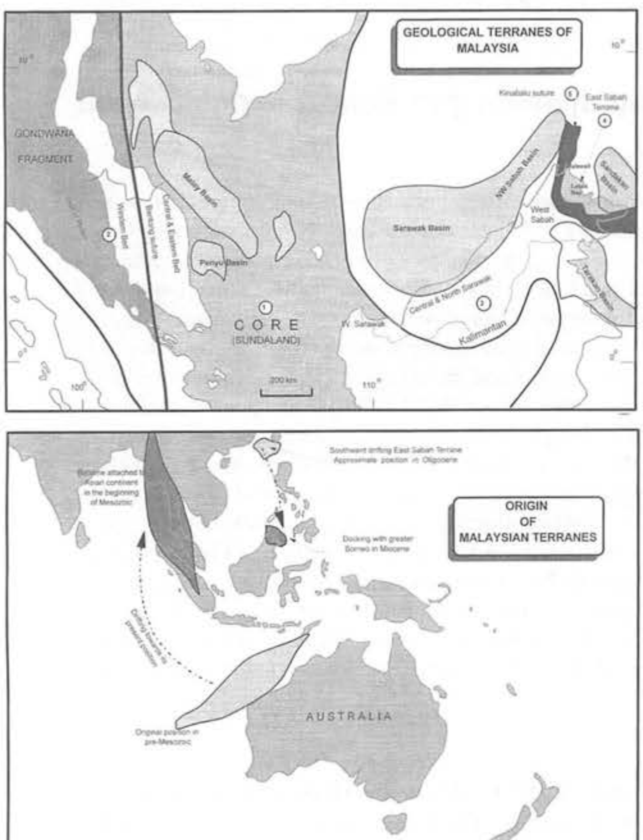

Figure 1: (Upper) The five geological terranes of Malaysia. (Lower) The origins of the Gondwana terrane and the East Sabah terrane.

Strait of Melaka to continue as the Bengkalis trough in the Central Sumatra basin. Field evidence were recorded from the Raub-Bentong-Manchis area, Pahang, and from SW Kelantan (Chakraborty and Metcalfe, 1987; Tjia 1987 & 1989; Tjia and Syed Sheikh Almashoor, in press). The Bentong suture separates the Western belt from the remainder of Peninsular Malaysia. This terrane became tectonically stabilised possibly by the end of the Mesozoic that coincided with peneplanation of Sundaland.

STRAIT OF MELAKA DEPOCENTRES

As result of exploration efforts by petroleum companies, about a score of small, elongated depressions filled with Cenozoic sediments have been mapped on the Malaysian side of the Strait of Melaka. Six wells have been drilled sofar that, that save for one minor gas find, were dry. The depocentres are dominantly half-grabens. Liew (1994, 1997) analysed proprietary reports and suggested that the depocentres can be grouped according to North-South tectonic belts in the North Sumatra and Central Sumatra basins, such as, (1) Tamiang/Yang Besar High-related grabens; (2) Asahan Arch/Kepulauan Aruah Nose-related grabens; (3) Pematang/Balam Trough-related grabens; and (4) Bengkalis Trough-related grabens. The grabens occupy regional, pre-Tertiary basement lows while the various belts are separated by regional basement highs. Liew further suggested that the en echelon arrangements of these N-S belts and the general northerly elongation of the fault depressions within the belts were produced by dextral wrenching of the Strait of Melaka corridor parallel to its NW-elongation. However, all evidence for wrenching along NW faults onshore Peninsular Malaysia indicate sinistral sense whose activity most probably ceased in Middle Eocene

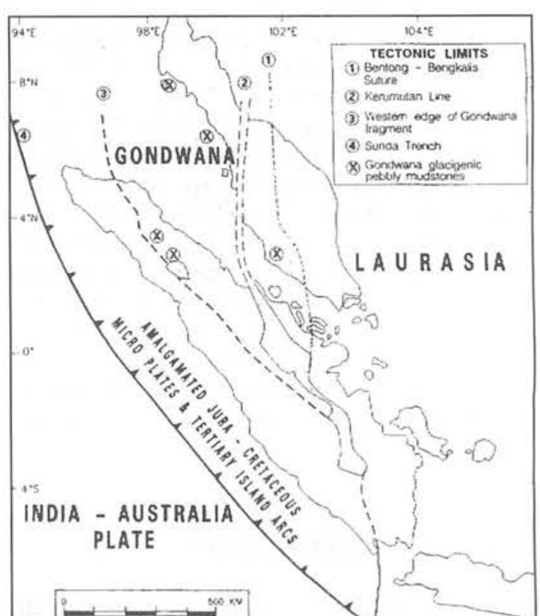

Figure 2: The distribution of Upper Carboniferous-Lower Permian pebbly mudstones in Southeast Asia.

time (Zaiton Harun, 1992), while similarly striking faults on Sumatra are all dextral and appear to have been active since at least the Middle Miocene. Since the N-S en echelon fault depressions began to fill with lower Miocene or older sediments, a serious time discrepancy is obvious between fault activity on the two sides of the Strait.

Map patterns strongly suggests en echelon arrangements of the faulted depressions (Figure 3). The Central Graben, the Southern Graben, and a few smaller grabens are left-stepping en echelon within a N-S belt, indicating dextral slip along that belt. Dextral slip is also shown by the en echelon arrays of faults associated with the Central Graben (Figure 4). To the west of this N-S belt are five strongly elongated grabens arranged en echelon in a NE-SW belt. Sinistral slip is indicated by the en echelon arrangement of the grabens. These two mentioned belts intersect at about 50 degrees. The bisectrice of this acute angle strikes N30°E and possibly represents the regional compression direction that is genetically related to the belts of en echelon grabens just described.

The stratigraphy of fault depressions in the northern Strait and that of the central and southern segments of the Strait are correlated with that of the petroliferous North Sumatra and Central Sumatra basins, respectively. In the northern Strait, the Palaeocene is considered as basement, overlain by Eocene-lower Oligocene Tampur carbonate. After an episode that produced an unconformity, followed Upper Oligocene continental deposition in restricted surroundings that subsequently became marine, then holomarine (Lower Miocene), and a regression marked by inner neritic to coastal sedimentation in the Middle Miocene. Another unconformity was followed by neritic deposition in the later part of the late Miocene, the environment progressing to coastal and inner neritic surroundings.

For the central and southern parts of the Strait, late Oligocene lacustrine strata rest upon undifferentiated basement. This depositional environment interspersed with fluvio-deltaic conditions was maintained until the end of the Miocene when a geological event produced an unconformity. This was succeeded by shallow-marine to coastal plain deposition in the Plio-Pleistocene.

The larger depocentres are filled with Cenozoic sediments ranging between about 1000 m to 4000 m. Three of the thicker sequences are 3300 to 4000 metres in the Johor, Angsa, Port Klang and Central grabens (Figure 5). The fault pattern at basement level in the Central Graben is distinctly en echelon and suggests an origin by dextral strike-slip along the graben's long axis. A NW-SE seismic line across the Johor Graben also shows evidence for wrench faulting (Figure 6).

The geology of the Strait of Melaka fault depressions is interpreted as follows. Structural control of the pre-Tertiary basement is by northerly trending faults and, as Liew (1994) pointed out, and the Cenozoic depocentres are preferentially located in regional basement lows. In the later part of the Oligocene, regional tension reactivated the

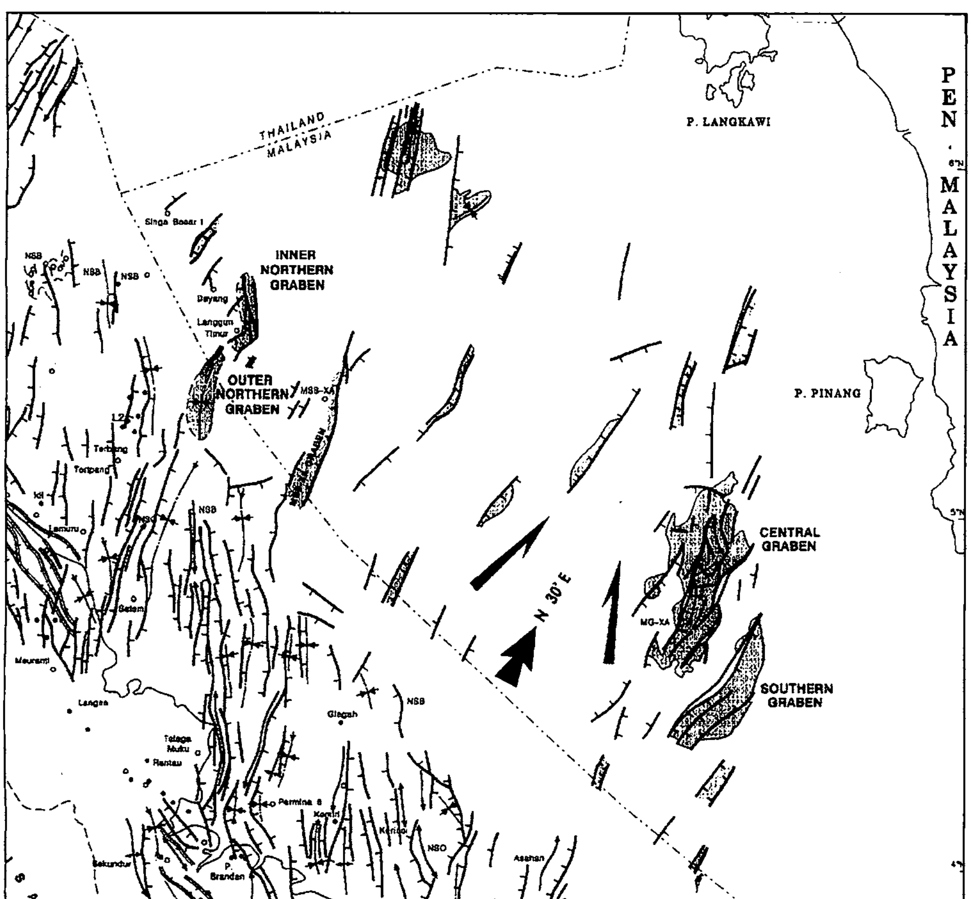

Figure 3: En echelon fault-depressions in the eastern side of the Strait of Melaka.

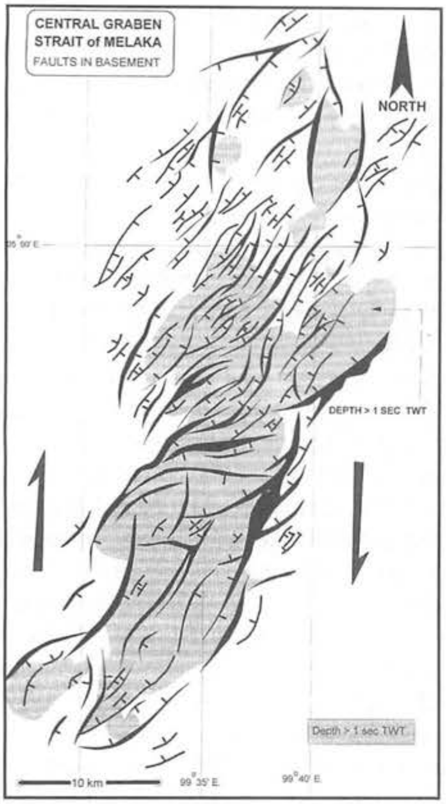

Figure 4: Fault pattern in the basement of the Central Graben, Strait of Melaka.

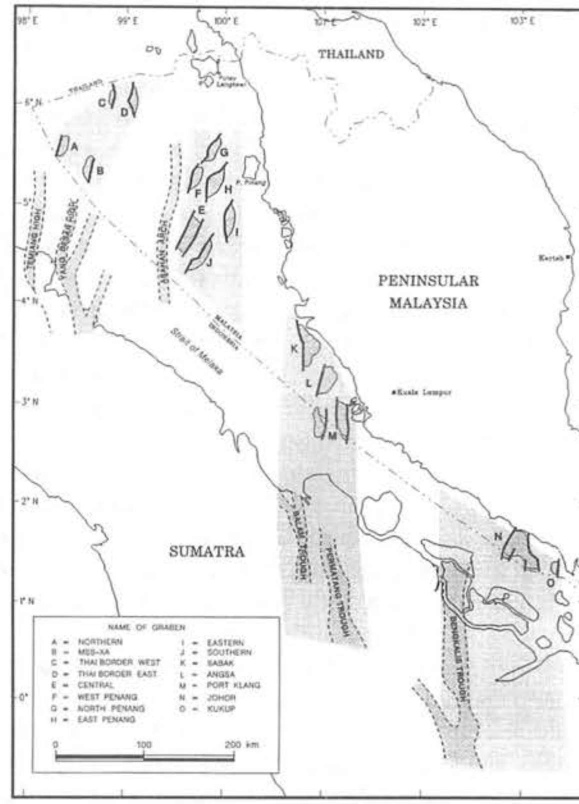

Figure 5: Fault-depressions in the Strait of Melaka. After Liew (1995)

basement fractures to produce grabens and half-grabens. Late Oligocene regional tension was not restricted to the Strait of Melaka region but is also apparent from the stratigraphy of the Malay and Penyu basins. For tension in the northern Strait region progressive counterclockwise rotation of Sumatra (including the rest of Sundaland) from a N-S orientation to more than 50 degrees counterclockwise was invoked by Davies (1984). The cause of CCW rotation probably resulted from the interplay between extrusion of the SE Asian continent and relative change in the collision angle between the Indian Ocean/Australian plate and Sundaland. Marine conditions prevailed in the north while in the centre and in the south the Miocene to Pliocene are represented by terrestrial, lacustrine and at the most coastal deposits. Only at the end of the Cenozoic marine conditions also reigned in these parts of the Strait.

ONSHORE PENINSULAR MALAYSIA

Raj *et al*. (1998) compiled information on 10 probable Cenozoic depocentres in Peninsular Malaysia. Their surface areas are in the order of a hundred square kilometres or less. Best described are those at Batu Arang, Selangor and at Nenering, Perak (Figure 7). The Lawin and Batu Arang depocentres appear associated with the Baubak (Bok Bak) and Kuala Lumpur fault zones, respectively. Gravity faults with throws exceeding 10 metres have been recorded, such as in the fanglomerate banks of Lawin. Syn- and/or post-depositional normal faulting is probably typical, examples having been described from Nenering and Batu Arang. Strata dips in excess of 30 degrees at Bukit Arang, Perlis, and also in the aforementioned depocentres, clearly indicate post-depositional disturbance. Generally bedding is only about 20 degrees and all known basins display sag structures without anticlines or domes. The basin fills range from minor to 300 metres with typical thickness of 100 to 200 metres. These are fluvial clastics, fanglomerates (boulder beds), lacustrine and paludal strata, coal and lignite being important at Batu Arang, Selangor, and at Bukit Arang, Perlis. Most of the sediments carry Neogene palynomorphs, but Ahmad Munif Koraini (1993) identified Eocene representatives from the Batu Arang beds. Uyop Said and Che Aziz Ali (1997) reported the presence of Aptian/Albian pollen from Nenering.

The Geological Survey of Malaysia (now Minerals and Geoscience Department of Malaysia) mapped Bouguer gravity anomalies of at least 10 mgal that suggest a N-S elongated, 30 km x 20 km, low-density rock body in the Teluk Datuk lowland of Selangor. Just offshore the Selangor coast line lies the northerly striking Klang Graben filled with Cenozoic sediments. The Teluk Datuk low-density rock unit could well represent young sediments.

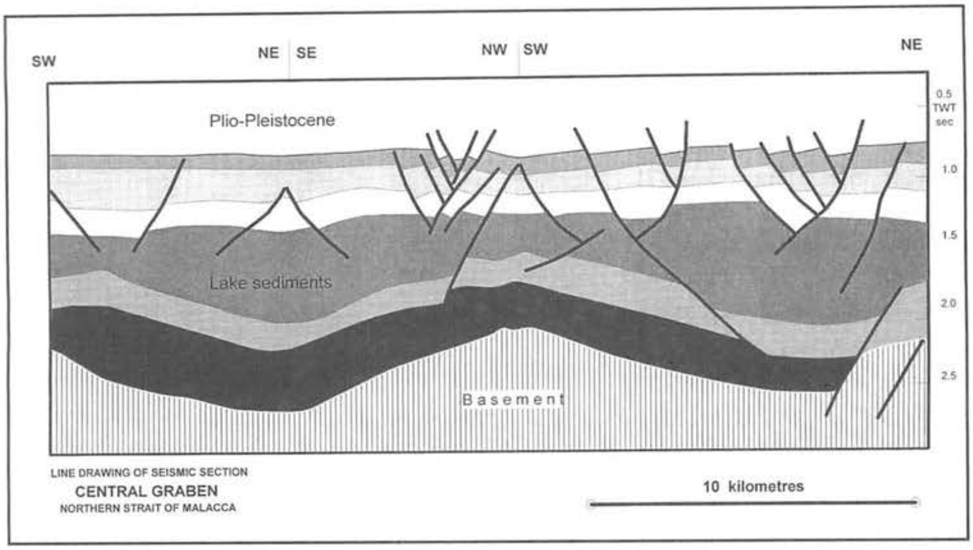

Figure 6: Line drawing of a seismic section showing probable flower structures in the Central Graben, Strait of Melaka.

SUNDA SHELF, NORTHERN SOUTH CHINA SEA

Malay Basin and Satellite Basins

The Malay basin is the largest among the hydrocarbon-bearing Cenozoic basins of the Sunda Shelf. It is 500 km long and 200 km wide. The regional trend is NW for its southern and central parts, but this changes into northerly for the North Malay basin.

Two main stratigraphic schemes are in use, one devised by EPMI (Esso Production [Malaysia] Incorporated) and the other by PETRONAS Carigali Sendirian Berhad (PCSB). The EPMI scheme is based on their so called global eustatic sea-level chart with some micropalaeontological control, while PCSB uses regional shale intervals in their division (Md Nazri Ramli, 1988).

The initial basin fill, or Oligocene/lower Miocene synrift deposits, was mainly non-marine. The lower Miocene/lower middle Miocene sequences were laid down under stable geological conditions. Sedimentation was terminated a strong regression, followed by a marine transgression in the Middle Miocene. Regression again prevailed in the late Middle Miocene that was soon succeeded by transgression towards the end of the Middle Miocene. A major unconformity within the Upper Miocene separates younger, essentially undisturbed sequences from the underlying deformed units. Exploration for placer tin provided stratigraphic information on the Pliocene/Pleistocene that began as marine beds followed by alluvial fills of channels incised into Pliocene and older rocks during the repeated subaerial exposures of the glacial episodes. The present seabed consists of up to 20-m thick blanket of green-grey marine clay (Aleva *et al*., 1973; Biswas, 1973).

It is widely accepted that Oligocene and younger Cenozoic strata in the Malay basin reaches 8 km thickness. A specially processed regional seismic line across the northern part of the basin shows gently dipping to horizontal stratification beneath suspected Oligocene down to 14 km depth (Figure 8). At Tok Bidan, a satellite depocentre of the Malay basin, redbeds below Lower Oligocene strata have been considered equivalents of the Jura-Cretaceous continental Tembeling/Gagau groups (see Liew, 1995).

The Malay basin is a large epicontinental depression. It is probably an aulacogen that together with the Penyu and West Natuna basins originated as rifts on top of an Upper Cretaceous Malay dome, centred about the triple junction of the three basins (Figure 9, Tjia, 1994). The geological age is suggested by widespread occurrence of late Cretaceous granitic plutons in the northern Sunda Shelf region. At the triple junction is thicker crust that may represent the root of differentiated mantle-plume material. The Malay dome is estimated at 1000 km across and its relics are the comparatively high positions of pre-Tertiary basement such as Peninsular Malaysia, Natuna, Anambas, Tambelan, Con Son islands, and adjacent shallow sea floor. At depths below 10 km the very steep to vertical contacts between basin-fill and basement may represent the rift surfaces (Figure 8). Rifting was most probably in the late Cretaceous, succeeded by basin subsidence until the end of Early Miocene. Six kilometres or more of pre-Oligocene sediments were accommodated in the rift. Also in pre-Oligocene time the postulated Axial Malay fault zone running in the basement along the basin's long axis moved in sinistral sense. This wrench motion created E-W half-grabens that became special depocentres and accumulated at least 8 km of Oligocene and younger sediments. The Axial Malay fault zone extended NW-ward as the Three Pagodas fault zone. Other NW-striking regional fault zones across the SE Asian continent are the Mae Ping (also known as Tonle Sap) and Red. On account of hard collision of the Indian subplate with Eurasia that began in Mid-Eocene time, Tapponnier *et al*. (1982) proposed that crustal slabs of SE Asia were differentially extruded along the 3 regional faults, the slab to the west of each NW regional fault moving farther south/southeast than its neighbour to the east of the fault. Differential expulsion thus produced sinistral slip sense on the large NW-faults. During middle-late Miocene the stress regime for the Malay basin became transpressional, possibly as result of reorientation of plate motions in the greater Indonesian region. Vertical structural inversions and reversals of wrench movements were common. Now the Axial Malay fault zone moved right-laterally. Inversion began in the south of the basin, where reverse faulting had occurred and progressed NW-ward. Reverse faulting has partly restored downthrows by up to a kilometre on former growth faults where vertical separation may have amounted to 2.5 km. Half-graben infills were deformed into anticlines whose E-W strikes were pre-determined by the orientation of the half-grabens. Regional transpression reached its peak at about 10 Ma but may have persisted until today. The latter would account for tightening of anticlines, across whose crests extensional faults have developed. The probable rift origin of the Malay basin implies that its initially restricted depositional environment was favourable to source rock accumulation and preservation. On account of the low position, migration of their hydrocarbons could have charged fractured basement that form horsts.

More recent discussions and interpretations of the tectonics and structural development of the Malay basin were provided in Khalid Ngah *et al*. (1996) and in Tjia and Liew (1996).

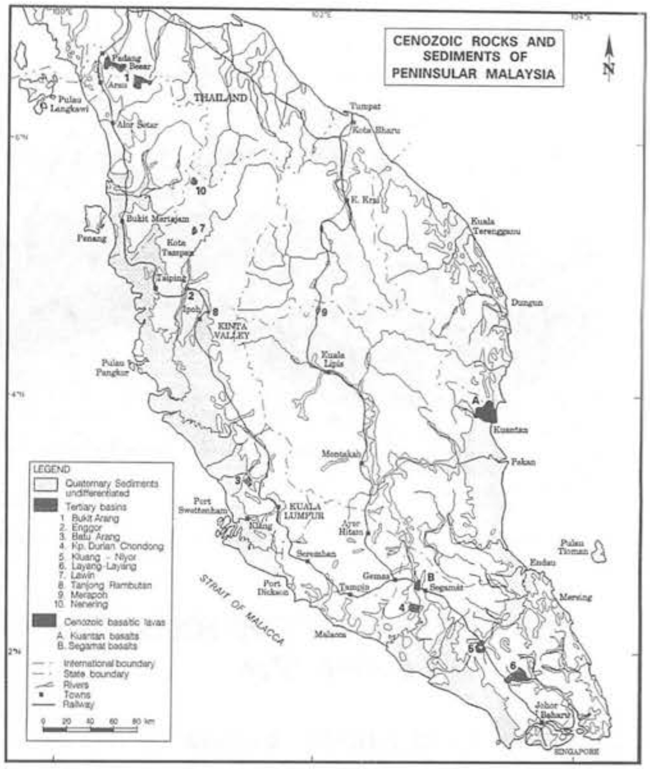

Figure 7: Cenozoic rocks and sediments onshore Peninsular Malaysia. After Raj *et al*. (1997)

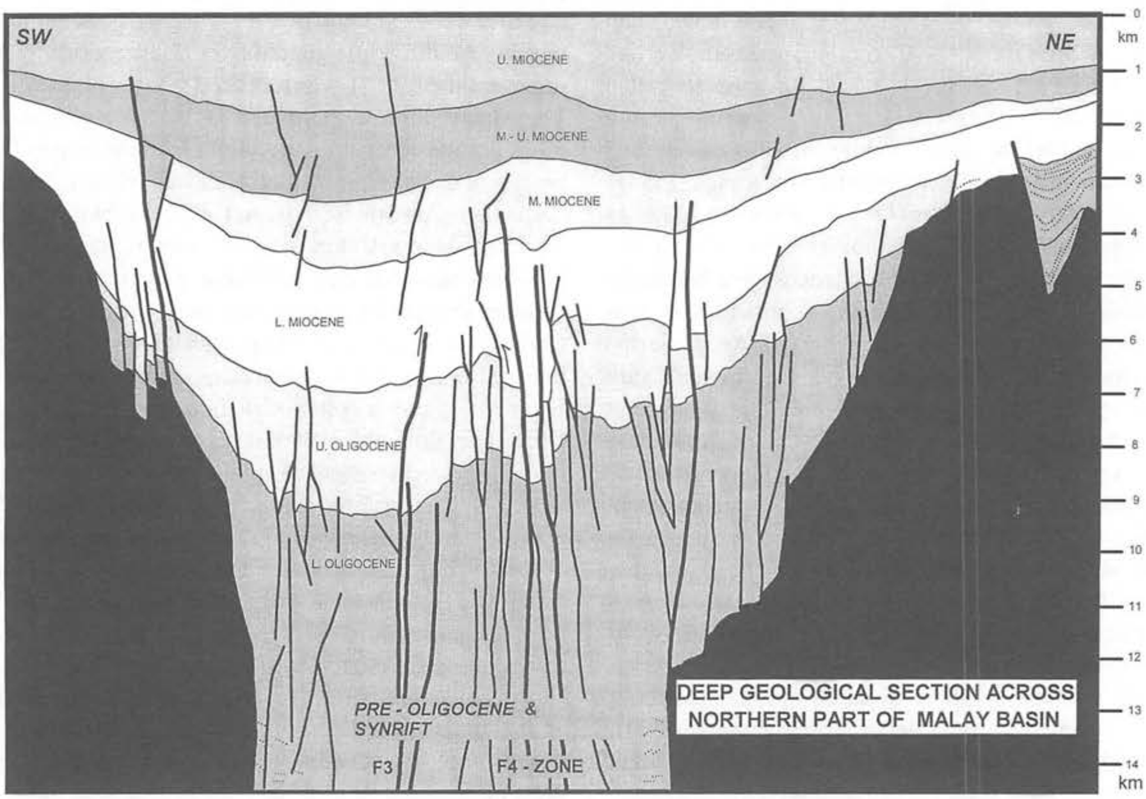

Figure 8: Interpreted structural section based on a regional seismic section across the northern part of the Malay basin.

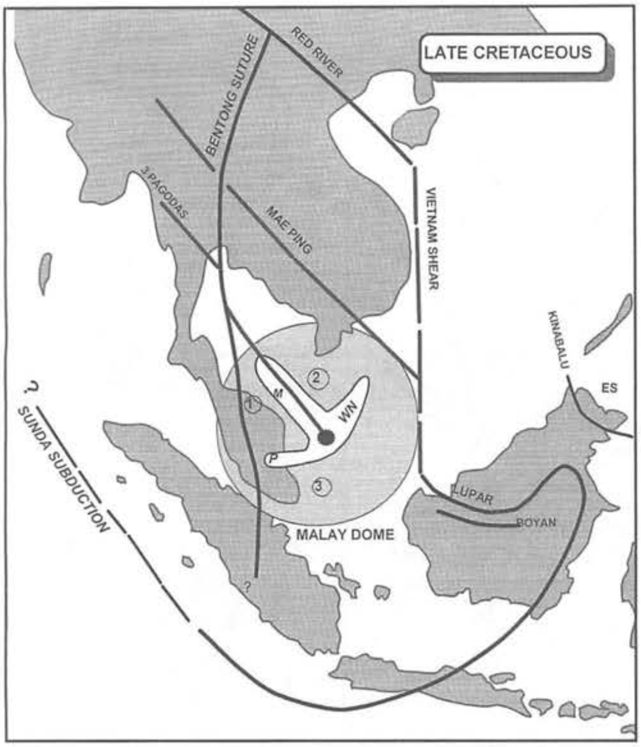

Figure 9: The Upper Cretaceous Malay Dome carrying the failed rift arms: Malay, Penyu and West Natuna basins. From Tjia (1994).

Penyu Basin

The Penyu basin is another failed rift arm of the Malay dome. The basin measures 160 km by 200 km and is somewhat elongated in E-W direction. Mazlan Madon *et al.* (1997) published the most current information. The surrounding basement highs of the basin have thin sedimentary cover, except over the Tenggol arch in the NE that is blanketed by about a kilometre of sediments. Faulting produced 10 major half-grabens in the pre-Tertiary basement. The Penyu basin is further divided by a regional, NW striking Rumbia fault. The western part is marked by E-W depocentres; the eastern part has WNW-ESE orientated depressions (Figure 10). The Rumbia fault is more than 100 km long and its heave is more than 2 km. Left-lateral separation of once contiguous structures suggest 20 km sinistral displacement. The E-W and en echelon sigmoidal fractures form a structural pattern that is believed to have resulted from sinistral wrenching on the Rumbia fault and other, currently unknown, NW-trending faults. Effects of compressional tectonics are subdued; seismic shows anticlinal features over the deepest parts of the Penyu basin. The WNW-ESE orientation of half-grabens in the eastern part of the basin very probably represent clockwise rotation of about 25 degrees by continued sinistral wrenching on the Rumbia fault.

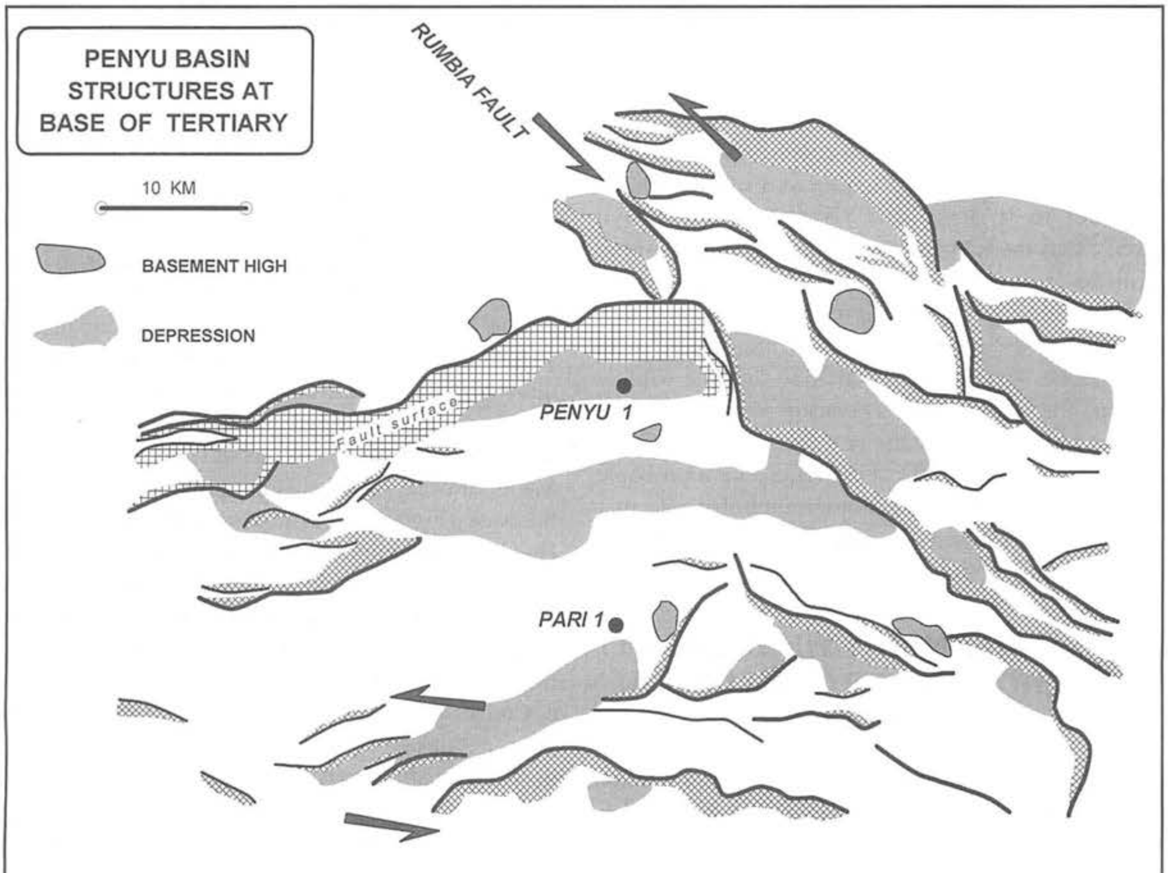

Figure 10: Penyu basin basement structures and interpreted sinistral wrench zones (arrows). From Khalid *et al.* (1996)

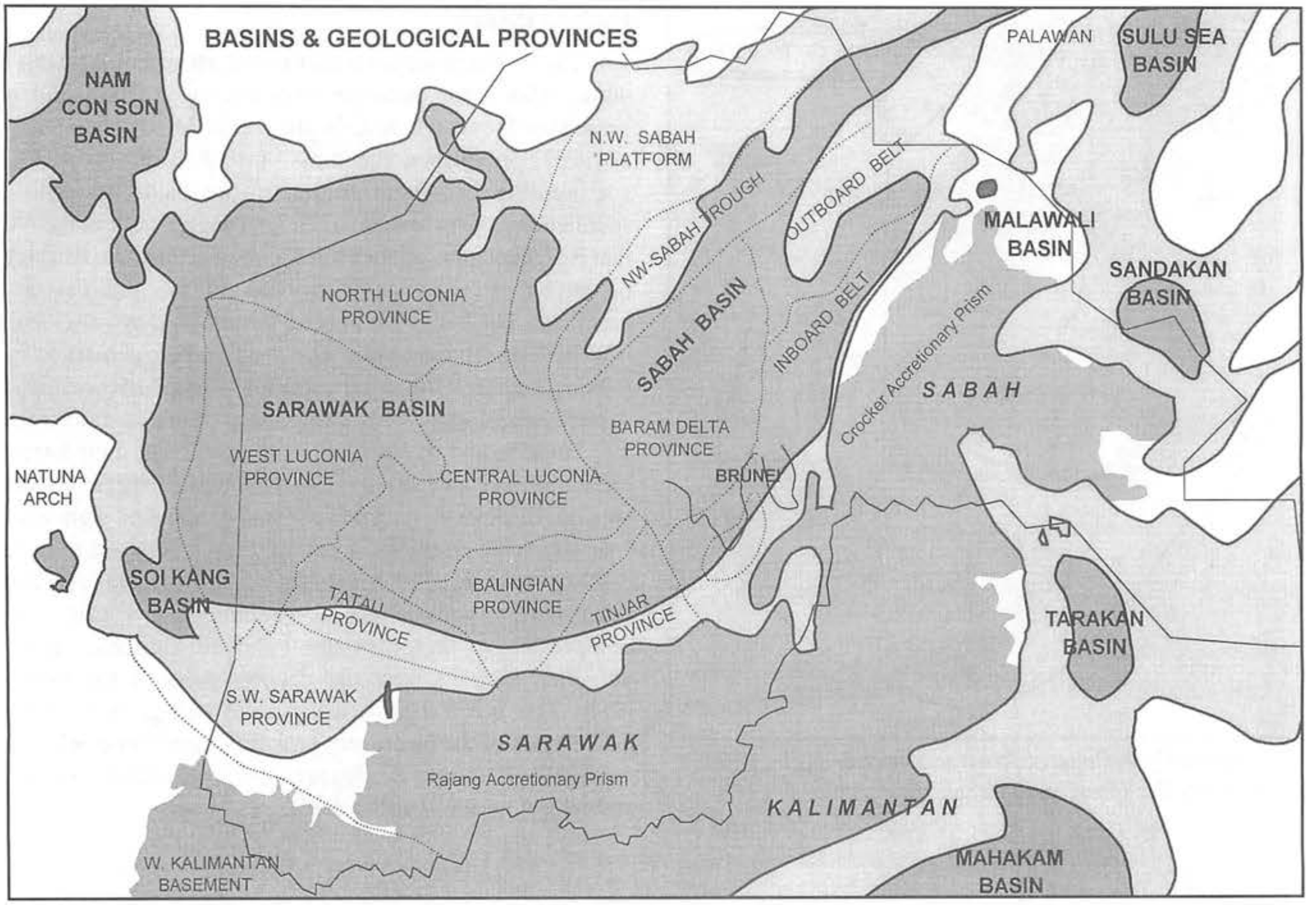

Figure 11: The petroleum provinces of Sarawak and Sabah.

The Cenozoic development of the Penyu basin began with an Oligocene trans(?)tensional regime and associated left-lateral wrenching on the Rumbia and other regional faults parallel to it. Lake and river deposits (Penyu Formation) filled the half-grabens. Major growth faulting is apparent. Tectonic uplift at the end of the Penyu Formation (end of Oligocene) developed a regional unconformity. Renewed subsidence in early Miocene time began with deposition of the Terengganu Formation and the Middle Miocene Pari formations, both as coastal plain sequences. Some of the faults were reactivated and normal faulting continued into the Middle Miocene. After that a probable transpressional event produced another unconformity that became the base of a shallow-marine sequence, the Upper Miocene-Pliocene Pilong Formation.

SARAWAK AND NORTHWEST SABAH BASINS (INCLUDING BARAM DELTA PROVINCE)

Together the Sarawak and Sabah basins form a large, crescent not unlike the head of a giant golf club and is concave to the north (Figure 11). The NW-striking West Baram Line separates the two basins. The West Baram Line is partially straddled by the Baram Delta depocentre.

Sarawak Basin

The Sarawak basin is 400 km long (North-South) and its width is 460 km in the west and 280 km in the east. Oligocene and younger sediments exceed 10 km thickness; the 5 km isopach of the main depocentre indicates N-S elongation (see CCOP map of 1991). The basin is bordered by the Vietnam Shear in the west, the Lupar Line in the southwest, the upper Cretaceous-Palaeocene Rajang fold-thrust belt in the south, the West Baram Line in the northeast, and the South China Sea oceanic basin in the north. Seven tectonostratigraphic domains have been recognised by the Shell Sarawak only the Tinjar province is entirely onshore Sarawak (Figure 11). The fundamental stratigraphy is by Ho (1978) and James (1984; updated and revised by Sandal, 1996) has discussed its tectonic development. The stratigraphy consists of cycles, each representing a major regressive sequence that is bounded by basin-wide transgressions. The *Southwest Sarawak Province* comprises a Cretaceous-Eocene volcanic arc with late Cretaceous granitic intrusives while its forearc was located to the north. Thrusting verged south. The *Rajang Fold-thrust Belt*, also known as the Rajang Accretionary Prism (RAP), comprises deep-water sediments, of which turbidites form a major portion. The RAP has been interpreted to comprise fault-bounded sequences that through subduction in southward direction have been progressively stacked into a more than 12 km thick wedge. It also contains post-subduction volcanics and associated intrusions such as at Usun Apau, Hose Mountains and others. The Lupar Line separates the RAP from the West Sarawak basement. The *Tatau Province* is marked by the presence of horsts and grabens. The Eocene Arip volcanics represent local volcanic activity. The *Tinjar and Balingian Provinces* comprise Upper Eocene and younger sediments resting unconformably upon the RAP. From late Eocene to earliest Miocene deep-water sedimentation prevailed; then the environment gradually became shallow marine. Local unconformities are common, which probably represent more vigorous progressions of the Luconia microcontinent in its southward advance. In early Miocene the microcontinent collided with the RAP, while at the same time active spreading of the South China Sea basin had ceased. Loading by the thrust packets and later in the post-subduction stage, isostatic compensation developed a depression at the leading edge of the Luconia block. The depression became filled with upper Palaeogene and Neogene coastal and shallow-marine strata of the Tinjar and Balingian provinces. The *Luconia Province* has a relatively stable base in the form of a microcontinent. It is believed that the microcontinent arrived from a northerly provenance. During its pre-collision drift on account of spreading of the South China Sea basin, the Luconia block coursed through clear waters free from terrestrial detritus, a condition that allowed the reef development and other carbonate buildups. Compressional deformation has only occurred at its leading edge, a narrow zone marginal to the Balingian Province. Post-collision detritus progressively spread northwestwards covering all carbonate structures except those in the far north such as the Luconia Shoals where buildups are still proceeding.

The issue of rotation of Borneo since the Cretaceous has been based on palaeomagnetic studies. While Haile *et al.* (1977) suggested that CCW rotation was completed before the Miocene, similar techniques applied by other workers on different rock samples from the island did not detect any Cenozoic rotation (see articles in the Journal of Southeast Asian Earth Sciences, Volume 8 (1-4), 1993). Patterns of well-bore breakouts (total of 31 wells at 19 locations in the Sarawak basin, Tjia and Mohd Idrus Ismail 1994) indicate localised rotations of stress regimes associated with wrench faults.

Magnetic lineations in the oceanic floor of the South China Sea basin document North-South opening between 32 Ma and 17 Ma (Taylor and Hayes, 1983). Briais *et al.* (1993) refined the development and pattern of this tectonic process and suggested that different spreading rates and spreading directions were associated with segmentation of the basin. Ru and Pigott (1986) proposed three stages of rifting alternating with two stages of spreading since early Cretaceous. They recognised (1) Late Cretaceous rifting along NE - SW direction, (2) Late Eocene rifting along E - W direction, and (3) late Early Miocene rifting along E - W direction.

The tectonic development of the Sarawak basin is on Figure 12. In pre-Late Cretaceous time sediments that later formed the "basement" of westernmost Sarawak (WS), Southwest Sarawak (SWS), Tinjar and Balingian (T&B) provinces, and the Rajang Fold-thrust Belt were respectively deposited next to the West Borneo continental block and adjacent to the leading edge of the Luconia Block which was then still part of the South China Plate. These sediments are postulated to rest on oceanic crust that eventually became subducted under the West Kalimantan continental block. During Late Cretaceous-Early Eocene, the Luconia Block separated from the Asian Plate that initiated the South China Sea basin opening. Southward subduction below the West Kalimantan block began to develop an accretionary wedge: the Boyan Melange of earliest Late Cretaceous age (Williams *et al.*, 1986). The Lupar Line coincides with the Late Cretaceous subduction trench. Late Cretaceous volcanics and granitoids in the West Kalimantan block accompanied that subduction. The ophiolitic Boyan Line, Lupar Line and the less developed Mersing Line (see below) are interpreted to mark pulses of rapid spreading of the South China Sea basin floor and that are also associated with periods of stronger tectonism. The stronger tectonic activities were probably responsible for large-scale "flaking-off" of the subducting oceanic crust. These off scraped mafic crustal flakes became incorporated in the accretion wedge and now crop our as ophiolitic masses and mafic bodies along the three tectonic lines mentioned earlier. After early Eocene, RAP strata contributed to further development of the Sarawak-West Kalimantan accretionary prism. The Lupar Line separates the RAP from the older Boyan Melange. In Late Eocene (and ?Oligocene) time another strong spreading pulse of the South China Sea floor became represented by the Mersing Line, along which a large mafic- ultramafic rock body forms Bukit Mersing (02° 35' N. 113° 10' E.). By Early Miocene, the South China Sea basin stopped spreading causing the Luconia Block to stop drifting. Cessation of regional compression resulted in isostatic adjustment that was expressed as further subsidence of the area of the Tinjar, Balingian and Luconia provinces, while the RAP rose and provided detritus to form thick Neogene deposits in the subsiding provinces.

The Sarawak basin thus overlies a convergent plate boundary between attenuated continental crust in the north and the Rajang Upper Cretaceous-Palaeocene accretionary wedge in the south. Thicker continental fragments associated with that thinned crust form the semi-stable areas of Luconia, Dangerous Grounds and Reed Bank have remained sufficiently high to favour reef growth from the Miocene onward. Wrench faulting on regional faults, especially that trend NW (Ismail Che Mat Zin 1997, 1998), may have developed subbasins (Acis and Balingian basins) but the fault kinematics and pattern have no bearing whatsoever to the shape of the Sarawak basin.

Baram Delta Province

The Baram Delta depocentre was especially addressed in two major publications (James, 1984; Sandal, 1996). It is separated from the Sarawak basin by the NW-striking West Baram Line and is further characterised by kilometres-thick, mainly Neogene, deltaic sediments. To the east of the West Baram Line deeper water persisted after early Miocene in contrast to shallow-marine and coastal environments to its west. The Baram Delta Province is shown to overlie the Rajang-Crocker accretionary prism on the landward side and on the sea side the province has subducted continental crust as base.

Northwest Sabah Basin

Two recent publications on the geology and development of the Northwest Sabah basin are by Tan and Lamy (1990) and by Hazebroek and Tan (1995). The Palaeogene development of the basin was described by Tongkul (1995). The basin is almost 200 km wide and 300 km long in NE direction. It consists of parallel rows of deeps separated by basement highs parallel to the long axis. The deep zone nearer to the onshore contains more than 12 km of Cenozoic sediments, while the two other deeps farther offshore are filled by about 10 km of sediments (see CCOP 1991). Six tectonostratigraphic provinces are identified. These are (1) the Rajang Group Fold-Thrust Belt, (2) Inboard Belt, (3) Baram Delta (described earlier in this article), (4) Outboard Belt, (5) NW Sabah Trough, and (6) NW Sabah Platform (Figure 11). The two phases of basin development (Hazebroek and Tan, 1995) comprise pre-early Middle Miocene deposition of generally deep-marine clastic deposits, and a post-early Middle Miocene clastic shelf/slope deposition that

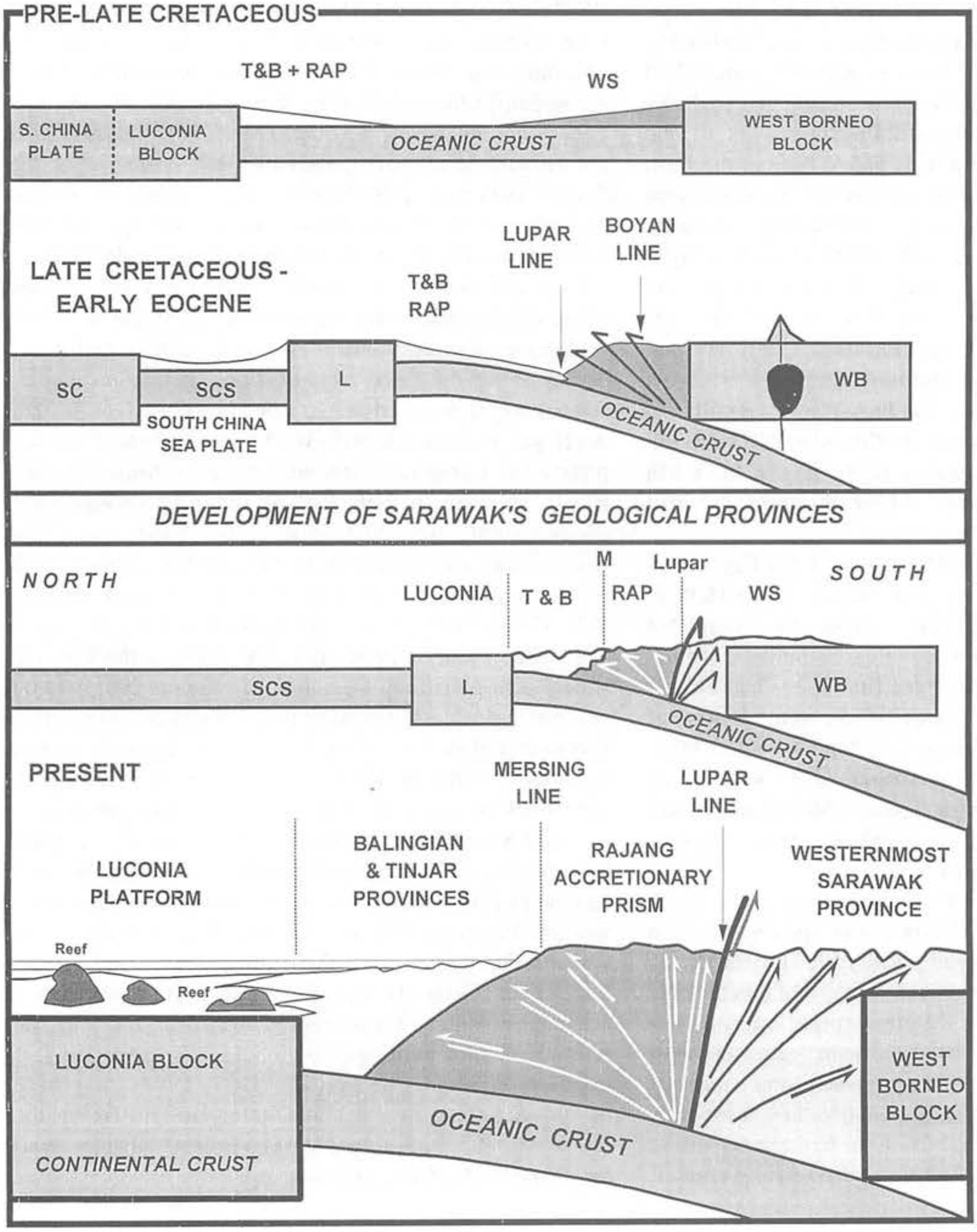

Figure 12: Structural development of the Sarawak basin. Key: L – Luconia, B – Balingian, T – Tinjar, RAP – Rajang Accretionary Prism, WS – Westernmost Sarawak.

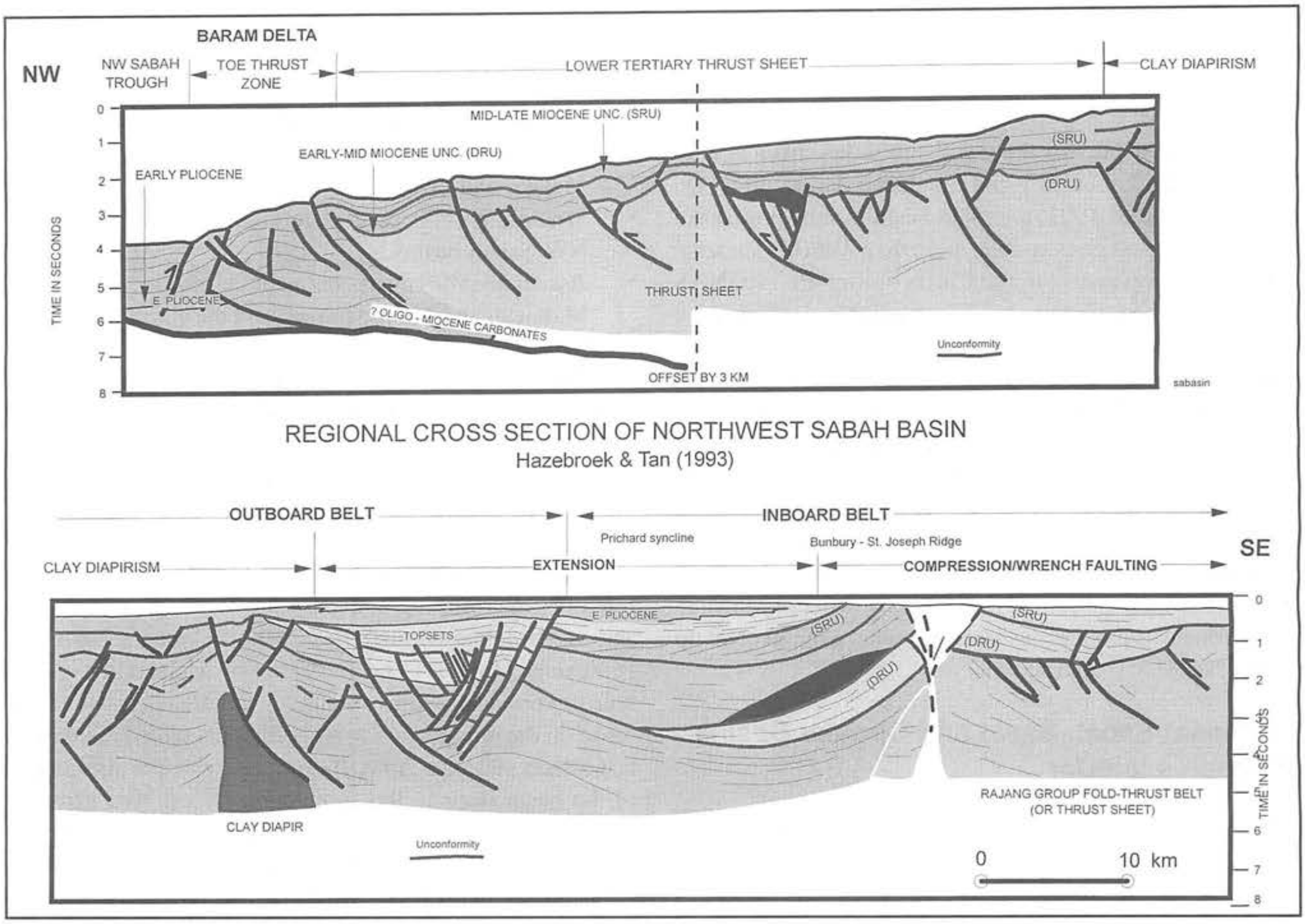

Figure 13: Regional sections across the NW Sabah basin. Simplified after Hazebroek and Tan (1993).

prograded NW-ward over the underlying sediment wedge and is separated from the latter by a major regional unconformity.

Hamilton (1979) proposed subduction from the northwest as consequence of spreading of the South China Sea basin. In this subduction system, the Crocker-Trusmadi fold-thrust zone is the accretionary prism, while the NW Sabah Trough is the surface expression of the subduction trench. However, no associated volcanism in Sabah's hinterland is known to exist.

Hazebroek and Tan (1995 provided the following information. The *NW Sabah Trough* is 80 km wide, 300 km long and in the SW ends against the Luconia Block of Sarawak. The seabed lies at -2800 m. The trough probably continues NE as the still active Palawan subduction Trench. The authors referred to seismic images that showed the trough as a downfaulted part of the NW Sabah Platform. On the SW side, the trough abuts against the "toe-thrust belt" of the Baram Delta which consists of upper Miocene to Recent sediments. From their tectonic section (their Figure 7a, p. 204) the trough appears as a passively formed depression relative to the deformed seabed of the toe-thrust zone.

The *Outboard Belt* is a complex of extensional as well as compressional structures, the latter being associated with wrench-faulting. Clay diapirs are also common.

The *Inboard Belt* consists of NNE-SSW tight and broken anticlines (the "Sabah Ridges") alternating with broad synclines. In seismic the anticlines are associated with flower structures. Deformation occurred in two stages: a major Late Miocene/Early Pliocene deformation and a more local Late Pliocene/Pleistocene phase. A 100-km sinistral separation of the Middle Miocene shelf margin was probably caused by wrenching in a N-S zone.

The *Crocker-Trusmadi fold-thrust belt* consists of Eocene to Oligocene turbidites that in the Ranau area are associated with olistostromes (Tjia 1988). In west Sabah tectonic vergence is NW, while in the Ranau area bivergent tectonic transport directions are believed to mark the Kinabalu Suture.

Figure 13 (Hazebroek and Tan's Figures 5a and 5b) shows two sections across the NW Sabah basin. The thick accumulations of the basin were produced by a NW-verging lower Tertiary thrust sheet that farther seaward pushes against the broad Baram Delta toe-thrust belt of mainly Neogene age, while upper Miocene and younger sediments fill depressions on the back of the thrust sheet and those on the toe-thrust. In short, the Sabah basin, like the Sarawak basin, straddles a collisional plate boundary that, when by Middle Miocene probable subduction ceased, all its oceanic crust had been consumed or incorporated in the Crocker-Trusmadi accretionary wedge. Younger Neogene sediments then prograded over the imbricated and overthrusted older sequences. Deposition was assisted by sagging of the sea floor on account of isostatic adjustments.

Northeast Sabah Basin

This basin consists of several subbasins (from NW to SE) Malawali, Labuk Bay and Sandakan depocentres. On the CCOP map of 1991, the main basin is shown to strike NE and its deepest parts contain more than 7 km of Cenozoic sediments, However, in the forthcoming PETRONAS publication (K.M. Leong pers. comm. 2000), the Northeast Sabah Basin comprises NE-striking subbasins alternating with similarly trending ridges and island/island groups: Palawan Island, Keenapusan Ridge, and Sulu Ridge. The tectonic lineaments of the Sulu Sea basin are long, NW-SE fracture zones transecting NE-SW ridge/island arcs and depressions (Schlueter *et al.*, 1996). PETRONAS combined the Sandakan and Labuk Bay depocentres into the Central Sabah basin. Tjia *et al.* (1990) have shown the onshore part of this basin as an aborted NE-SW rift of Middle Miocene age. Rifting was probably associated with the initial breakup of the East Sabah microcontinent.

Southeast Sabah Basin and Circular Basins of Sabah's Interior

This comprises the deeper Tidung (or Northern Tarakan subbasin) in the west and a platform in the east. The depocentre is elongated NE and is 20 km x 50 km in dimensions. Thrust faulting verging NE-ward is thought to have occurred on both sides of the depocentre. Towards NW the Tidung depression adjoins two large, Neogene circular basins of Sabah's interior: the Malibau and Maliau. Collenette (1965) suggested that these three basins, Tidung, Malibau and Maliau became segmented from a single basin by a late Pliocene compressive event that also produced the thrust faults on some of the northeast rims of the basins. Tjia *et al.* (1990) believed that the Tidung basin is associated with aborted rifting of the East Sabah platelet.

I mapped numerous NW-SE fracture zones across Sabah on proprietary synthetic aperture radar images. Strike-slip motion is very likely in view of the linearity of the fracture zones. The slip sense has been sinistral. Field mapping and aerial photo interpretation of the Maliau basin showed that its general structure conforms to a sag depression without appreciable compressive features. It is therefore more likely that the thrust faults at some of the basin rims only represent local deformations associated with wrench motion of the regional NW fracture zones.

The origin of the circular Neogene basins of Sabah's interior has been ascribed to clay diapirism, extraterrestrial impact, or subsidence controlled by intersecting regional NW and NE fault zones.

CONCLUSIONS

The Cenozoic tectonic setting of the Malaysian basins may be classified in the following manner:

- Located in the interior of semicratonic continental crust: the Malay and its satellite basins and the Penyu basin.
- Located in marginal belts of semicratonic continental crust: many small, faulted depressions in the Strait of Melaka and onshore Peninsular Malaysia.
- Straddling collisional plate boundaries: Sarawak and NW Sabah basins.
- Associated with microcontinent: Sandakan, Labuk Bay, Malawali and Tidung basins, and the circular basins of Sabah.

The Cenozoic basin development in Southeast Asia shows the following pattern. Rifting, thermal subsidence and modification by transtensional and/or transpressional wrench faulting are the tectonic processes that operate on depressions underlain by continental crust. The crust could belong to large plates or represent a microcontinent. Where wrench faulting is the main reactivator of basement fractures, the resulting pullaparts are of modest dimensions and of moderate depths. The onshore Tertiary basins of Peninsular Malaysia and the Strait of Melaka are of this type. Inverted structures are the rule, as are reversals of slip sense on the wrench faults. At collisional plate boundaries, large depressions are initially formed by active subsidence of the basin floor in the subduction trench. The growing accretionary prism on the land ward side of the trench wall enhances the basin depth. After subduction ceases, isostatic adjustments depresses the basin further, increasing its holding capacity. The origin and development of the circular basins of Sabah are unresolved issues. Their main features include the predominantly extensional character shown by their structures, rounded planimetric outline, and kink-like geographical distribution of which the ends are in Sandakan Bay and at Cowie Harbour.

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